

## DETECTORS FOR NEW NEUTRINO EXPERIMENTS

MAURY GOODMAN

*Argonne National Laboratory*

*Argonne IL 60439, USA*

*E-mail: maury.goodman@anl.gov*

There has been great progress in understanding the neutrino sector in the last few years. One mixing angle has not yet been measured,  $\theta_{13}$ . I will review detectors for the current round of long-baseline neutrino oscillation experiments, for future long-baseline off-axis detectors, and for two detector experiments at nuclear reactors.

### 1. Introduction

In the last few years we have seen remarkable progress in understanding the neutrino. Compelling evidence for the existence of neutrino mixing and oscillations has been presented in experiments using neutrinos from the atmosphere<sup>1,2</sup>, from the sun<sup>3</sup>, from reactors<sup>4</sup> and from accelerators<sup>5</sup>. Arguably, the most compelling task facing the neutrino community is to measure a non-zero value of  $\theta_{13}$ . If this is non-zero, then future searches for CP violation and matter effects are possible. There are two main ways to search for a non-zero value of  $\theta_{13}$ . They are new detectors in long-baseline neutrino beams, which might be put about 2 degrees off the center of the beam, and new reactor neutrino experiments with 2 detectors, one near and the other about 2 km away.

### 2. Current Long-Baseline Neutrino Experiments

A current program of long-baseline neutrino experiments includes the K2K experiment in Japan, which has been running since 1998, the NuMI/MINOS program at Fermilab, which is expected to start in 2005, and the CNGS program at CERN which will start in 2006. Accelerator beams consist mostly of muon neutrinos ( $\nu_\mu$ ) which are made when pions and Kaons decay. The dominant oscillation mode, which depends on the angle  $\theta_{23}$  is  $\nu_\mu \rightarrow \nu_\tau$ . All three experiments expect to measure a change in the number and distribution of  $\nu_\mu$  as a result of this oscillation. In addition,

CNGS hopes to measure  $\nu_\tau$  appearance.  $\nu_\tau$ 's would be present in all three experiments, but the production of  $\tau$ 's in K2K and MINOS is expected to be suppressed by kinematic thresholds. All three experiments will also have some sensitivity to  $\theta_{13}$  by looking for  $\nu_\mu \rightarrow \nu_e$  oscillations manifested by electron appearance. This is because

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2(\Delta m^2 L/4E) \quad (1)$$

Currently  $\Delta m^2$  is near  $2.0 \times 10^{-3} \text{eV}^2$  and  $\theta_{23}$  near  $45^\circ$  from atmospheric neutrino measurements, but  $\theta_{13}$  is unknown, limited by the Chooz reactor neutrino experiment as a function of  $\Delta m^2$ .

One long-baseline neutrino oscillation experiment is currently running, K2K from the 12 GeV PS at KEK to Super-Kamiokande. The remarkable Super-Kamiokande experiment is a water Cerenkov detector, arranged in a large stainless steel cylinder 37 m high by 34 m diameter. It ran for five years with high (40%) phototube coverage until it stopped for maintenance in August 2001. At the time, the tank was drained and some bad phototubes were replaced. While it was refilling, a tube imploded, causing a chain reaction which destroyed more than half of the phototubes. Since then it has been rebuilt with approximately 20% phototube coverage. Extensive tests were undertaken right after the accident to understand the mechanism. It was determined that a similar incident involving the propagation of a shock wave could not take place if the phototubes were placed in a container with a small hole for water to get in and out. Thus the remaining phototubes were enclosed in newly designed vessels with a 13 mm acrylic front and a 5 mm fiberglass back molded in a shape similar to the phototubes. The detector was rebuilt and filled in October 2002, and is once again running. A beam from KEK is also running again. There have been less than 100 fully contained events in K2K, which should double.

The MINOS collaboration has built a detector in the Soudan mine in Minnesota to measure neutrinos produced by the NuMI beam at Fermilab. MINOS has chosen a magnetic iron sampling calorimeter for both its near and far detectors. Both detectors consist of 2.54 cm steel absorber plates and plastic scintillator planes. The planes contain strips of extruded scintillator which are 4.1 cm in width, and up to 8 meters long, with a wavelength shifting fiber carrying light to a Hamamatsu M16 phototube. By reading out both ends of the fiber, ionizing radiation is measured.

The CERN neutrino program is aiming a high energy beam at two detectors in Italy's Gran Sasso Lab. ICARUS is a very-high resolution liquid argon time projection chamber, and OPERA is made from a lead-

emulsion sandwich. A 600 ton version of ICARUS has been built and tested, with plans for 3000 tons. OPERA will measure evidence for the production of  $\tau$  decays from  $\nu_\tau$  charged current interactions produced after oscillations by seeing evidence for a tau kink in photographic emulsion. They expect a signal of  $18.3 \times [\Delta m^2 / (3.2 \times 10^{-3} eV^2)]^2$  events with a background of 0.57 events in 2 years.

### 3. Future Off-axis Long-Baseline Neutrino Experiments

#### 3.1. JPARC

The Japanese Particle Research Center (JPARC) is a new 50 GeV proton synchrotron being built in Tokai. A neutrino beam is being planned. In a first phase the accelerator would operate at 0.77 MW, but an upgrade to 4 MW is being considered. The 22.5 kiloton Super-Kamiokande detector is 295 km away, and the beam could be built to be simultaneously a few degrees off axis to that experiment and to the proposed site for a 1000 kiloton Hyper-Kamiokande detector in Tochibora. With a 5 year run of JPARC, and the proposed 2 degree off-axis beam, JPARC $\nu$  would be able to measure  $\theta_{13}$  or set a limit on  $\sin^2(2\theta_{13}) < 0.006$  at 90% CL. The Hyper-Kamiokande detector would be similar in design to Super-K, using large 50 cm diameter Hamamatsu phototubes.

#### 3.2. NuMI off-axis

A proposal is being developed for an off-axis experiment using the NuMI beam at Fermilab.<sup>6</sup> Any detector would be built near the surface of the earth, about 10 km away from the center of the NuMI beam. The detector should have a mass of 50 Kilotons, and be sensitive to 1 GeV electron showers. The passive detector is planned to be 7 sheets of 2.5 cm particle board between readout planes. Active detector technologies being considered are resistive plate chambers and liquid and solid scintillator.

To reduce costs from the MINOS experience, the fibers in a scintillator detector would be read out by Avalanche Photo Diodes (APDs), a low gain solid state detector with high quantum efficiency built onto a chip. The cost per channel in bare die form in the quantities appropriate for this experiment (600,000) is \$2.70 per channel, to be compared with a cost of about \$12 for similar quantities of multi-channel photomultiplier tubes. The APD quantum efficiency is 85% in the wavelength region of interest compared to 10% for a PMT with bi-alkali photocathode.

The liquid scintillator design is for 14.4 m long multicell extrusions of PVC, each containing 32 cells of width 3.75 cm. The cells would be 3 cm thick along the beam direction. A looped fiber would be inserted in each cell and an end-cap would be glued on one end, with a manifold/optical connector assembly at the other. There are no critical tolerances, such as positioning of the fiber.

One idea to standardize and stack large modules of detectors is to build them in standard shipping containers which are used throughout the shipping industry on trucks, trains and internationally on large ships. There is an ISO standard for these containers and as a result of the trade imbalance, there is a large excess of them in the United States.

#### 4. Reactor Experiments

From the discovery of the neutrinos by Reines and Cowan<sup>7</sup> at Savannah River to the evidence for  $\bar{\nu}_e$  disappearance at KamLAND<sup>4</sup>, reactor neutrino experiments have studied neutrinos in the same way – observation of inverse beta decay with scintillator detectors. Since the signal from a reactor falls with distance  $L$  as  $1/L^2$ , as detectors have been moved further away from reactors, it has become more important to reduce backgrounds. That can be done by putting experiments underground; and experiments one kilometer or more away from reactors (Chooz, Palo Verde and KamLAND) have been underground.

The KamLAND experiment measured a 40% disappearance of  $\bar{\nu}_e$  presumably associated with the 2nd term in Equation 2:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong -\sin^2 2\theta_{13} \sin^2(\Delta m_{atm}^2 L/4E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m_{12}^2 L/4E) + 1 \quad (2)$$

The Chooz and Palo Verde data put a limit on  $\theta_{13}$  (through the first term in Equation 2) of  $\sin^2 2\theta_{13} < 0.1$ . Those experiments could not have had greatly improved sensitivity to  $\theta_{13}$  because of uncertainties related to knowledge of the flux of neutrinos from the reactors. They were designed to test whether the atmospheric neutrino anomaly might have been due to  $\nu_\mu \rightarrow \nu_e$  oscillations, and hence were searching for large mixing.

New experiments<sup>8,9</sup> to look for non-zero values of  $\theta_{13}$  would need the following properties: 1) two or more detectors to reduce uncertainties to the reactor flux 2) identical detectors to reduce systematic errors related to detector acceptance, 3) carefully controlled energy calibration, 4) low backgrounds and/or reactor-off data.

In Equation 2, the values of  $\theta_{12}$ ,  $\Delta m_{12}^2$  and  $\Delta m_{atmo}^2$  are approximately

known. In Figure 1, the probability of  $\bar{\nu}_e$  disappearance as a function of  $L/E$  is plotted with  $\theta_{13}$  put at its maximum allowed value. Note that CP violation does not affect a disappearance experiment, and that matter effects can be safely ignored. The large variation in  $P$  for  $L/E > 10$  km/MeV is the effect seen by KamLAND and solar  $\nu$  experiments. The much smaller deviations from unity for  $L/E < 1$  km/MeV are the goal for an accurate new reactor experiment. The detectors are planned to be large volumes of liquid scintillator 25-100 tons, similar to the 10 ton Chooz experiment, but smaller than the 1100 ton KamLAND detector.

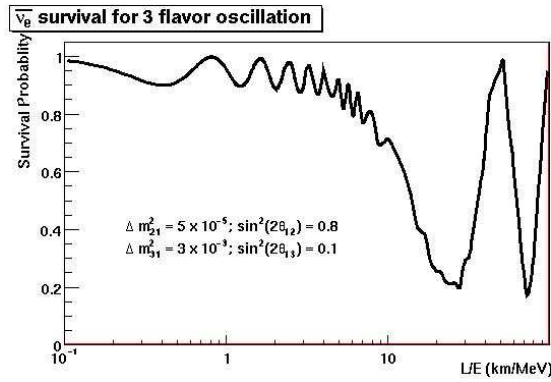


Figure 1. Probability of  $\nu_e$  disappearance versus  $L/E$  for  $\theta_{13}$  at its current upper limit

## References

1. Y. Fukuda et al., Phys.Rev.Lett. 81 (1998) 1562-1567.
2. D. Casper et al., Phys. Rev. Lett. 66 (1991) 2561; R. Becker-Szendy et al., Phys. Rev. D46 (1992) 3720; K.S. Hirata et al., Phys. Lett. B205, (1988) 416; K.S. Hirata et al., Phys. Lett. B280, (1992) 146; M. Sanchez et al., to be published by the Soudan 2 collaboration; M. Abrosio et al, Phys. Lett. B434 (1998) 451.
3. Ahmad et al., Phys. Rev. Lett. 89 (2002) 011301.
4. Eguchi et al., Phys. Rev. Lett. 90 (2003) 021802.
5. Ahn et al., Phys. Rev. Lett. 90 (2003) 041801.
6. D. Ayres et al., Letter of Intent to build an Off-axis detector to study  $\nu_\mu \rightarrow \nu_e$  oscillations with the NuMI Neutrino Beam, August 2002, Fermilab Proposal 929.
7. C.L. Cowan et al., Science 124, 103 (1956).
8. Y. Kozlov et al., Nucl.Phys.Proc.Suppl. 87 (2000) 514-516.
9. H. Minakata et al., hep-ph/0211111.